

SNS 110040300-TR0001-R00

Poison Depth Sensitivity Studies for the SNS Water Moderator

A U.S. Department of Energy Multilaboratory Project

S P A L L A T I O N N E U T R O N S O U R C E

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This document describes the variation in decoupled poisoned water moderator performance when using different gadolinium poison depths. The sensitivity calculations are performed relative to the SCT base case described more fully elsewhere.¹

1 Model Description

The base configuration we denote SCT includes four moderators, two of which are viewed from both sides. All moderators have nominal viewed faces of 100 mm (horizontal) by 120 mm (vertical). The inner reflector (out to a radius of ≈ 320 mm) is beryllium and is cooled with heavy water. This inner reflector is surrounded by heavy water-cooled stainless steel. Table 1 summarizes relevant characteristics of the target station configuration used for this set of calculations. Although the SNS is designed for 2 MW operation as shown in Table 1, the initial construction

Proton Energy	1 GeV
Pulse Rate	60 Hz
Average Power	2 MW
Energy per pulse	34 kJ
Proton Beam Shape	rectangular
Proton Beam Size	200x70 mm ²
Proton Pulse	$\delta(t)$
Target	Hg
Inner Reflector	Be
I.R. Coolant	D ₂ O
Outer Reflector	SS
O.R. Coolant	D ₂ O

Table 1: Target station parameters used in calculations. All normalizations are performed per 34 kJ-pulse.

will provide 1.44 MW operation. As our past calculations are normalized for 2 MW operation, we present these calculations with that same normalization.

Figure 1 illustrates and Table 2 summarizes the moderator configuration. The top upstream moderator is

Beamline	Moderator Location	Moderator Material	T (K)	Decoupling Material	Poison Material	Poison Depth (mm)
2	TU	H ₂	20	Cd	Gd	29.6
11	TU	H ₂	20	Cd	Gd	29.6
5	TD	H ₂	20	—	—	—
14	BD	H ₂	20	—	—	—
8	BU	H ₂ O	300	Cd	Gd	14.75
17	BU	H ₂ O	300	Cd	Gd	24.75

Table 2: Moderator summary. H₂ is 20 K supercritical, modeled as liquid parahydrogen at supercritical density.

cadmium-decoupled hydrogen (assumed to be 100% parahydrogen) at 20 K and has curved viewed surfaces. The moderator material has a maximum thickness of 60 mm, and an average thickness of about 55 mm. The moderator is (in the base case) poisoned at the centerline with gadolinium 0.8 mm thick and is viewed from both sides.

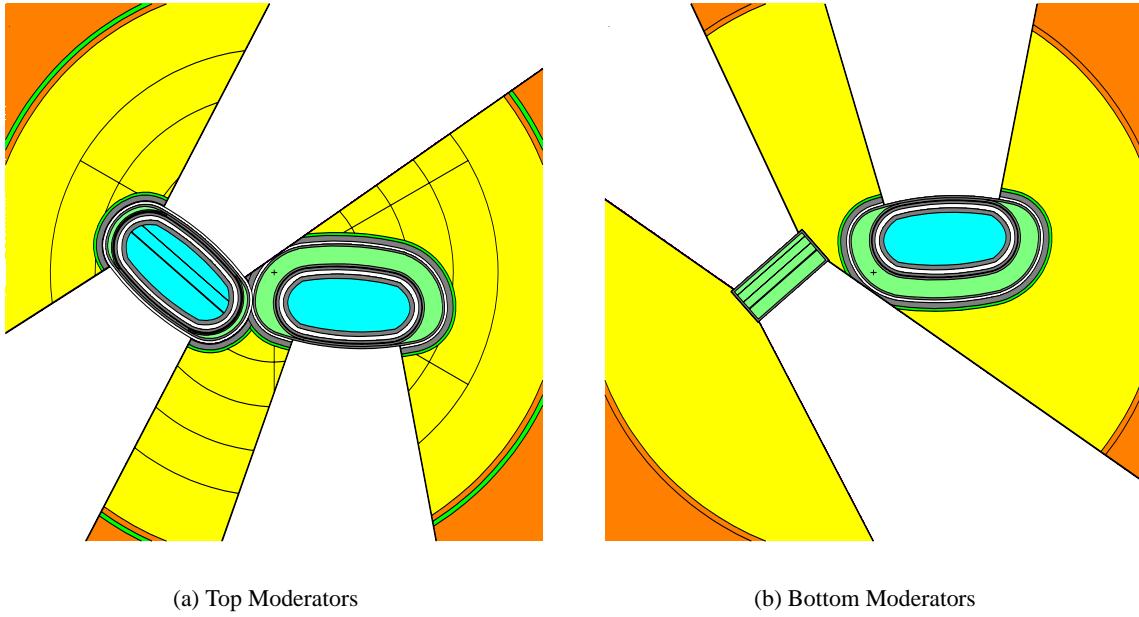


Figure 1: SNS moderator configuration. Elevations shown are the centers of the upstream moderators. Protons enter from the left. Beamlines are numbered counterclockwise beginning at the proton beam.

The top downstream moderator is fully coupled unpoisoned hydrogen (again parahydrogen) at 20 K, and is viewed from one side only. This moderator also has a curved viewed surface, with maximum thickness of 60 mm, and an average thickness of about 55 mm. This moderator also has approximately 20 mm of light water surrounding it as premoderator. The bottom downstream moderator is identical to the top downstream moderator. The bottom upstream moderator, the one varied for this study, is cadmium-decoupled water at 300 K with flat viewed surfaces. The moderator material is 40.5 mm thick, and is assymetrically poisoned with gadolinium 1 mm thick. This moderator is viewed from both sides. These poison depth sensitivity calculations concern only the bottom upstream moderator.

2 Calculational Techniques

The simulations reported are the results of calculations using the MCNPX code from LANL (version 2.1.5).² The spectral intensities shown result from calculations using point detector tallies located 10 m from the viewed surface of the moderator. Artificial collimating masks between the point detector locations and the moderator surfaces limit the tallied view of the moderator to a 100 mm horizontal by 120 mm vertical view of the moderator, centered on the viewed face. The emission time distributions (pulse shapes) come from current tallies on the viewed surface of the moderator material, and are averaged over 2π steradians. Weight windows to accelerate the pulse shape calculations were generated by separate iterative runs using MCNPX in parallel mode on a large cluster of machines with a neutron-only source term. MCNPX runs using these weight windows produced the reported results, which have further been scaled (from the point detector calculations) to correspond to the peak intensity coming off of the moderator face in the normal direction, rather than the average over 2π steradians. Each moderator requires a unique set of weight windows, and thus a unique set of runs. In this set of sensitivity calculations, we generated a single set

of weight windows and used them for each of the different poison depth calculations on the water moderator.

3 Observations

Exhaustive plots of spectra, emission time distributions, and various pulse shape metrics appears in Appendix B. We repeat some of that data here as illustration to our observations. The beam intensity and a metric (full-width at half-maximum) for the width of the energy-dependent pulse shape as calculated for a decoupled poisoned water moderator appear in Figure 2. Note that the nominal SCT water moderator poison depths are 15 mm and 25 mm.

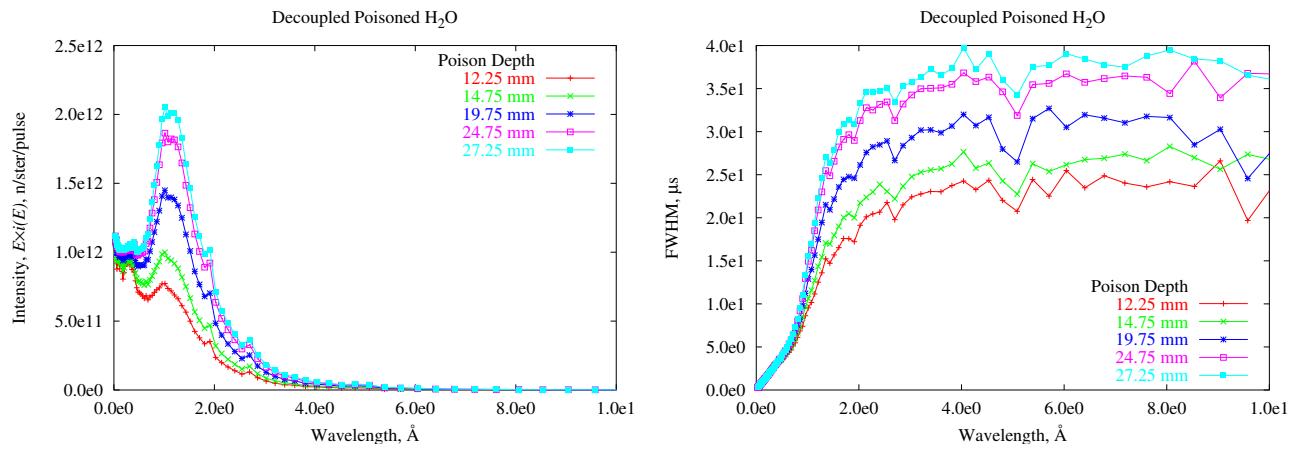


Figure 2: Intensity and pulse widths (FWHM) for a decoupled water moderator with different poison depths. The nominal poison depths for the SCT base case water moderator are 15 mm and 25 mm.

We clearly see significant differences between the moderator performance calculations made for different poison depths. The differences are relatively straightforward and predictable, with deeper poisoning giving greater peak intensity, greater integrated intensity, and greater pulse width, and a slower exponentially decaying tail (see Figure 3). Selection of the appropriate poison depth for a given instrument will require deeper instrument-based optimization studies, and likely compromises between the different instruments viewing the same surface of a moderator. It is worth noting that, for the water moderator, the poison depth significantly changes the long-time asymptotic behavior of the pulse shape (often referred to as the “tails”). This is a demonstration of the thermalizing nature of a water moderator, where the deeper poison increases the moderator storage time (see Figure 4(a)). Additional demonstration of the thermalizing nature of a water moderator comes from the “equilibrated” behavior of the pulse shape at lower energies as shown in Figure 4(b). Finally, further demonstration of this thermalizing nature comes from an examination of the RMS deviation of the pulse width, as shown in Figure 5, showing large differences as a function of poison depth.

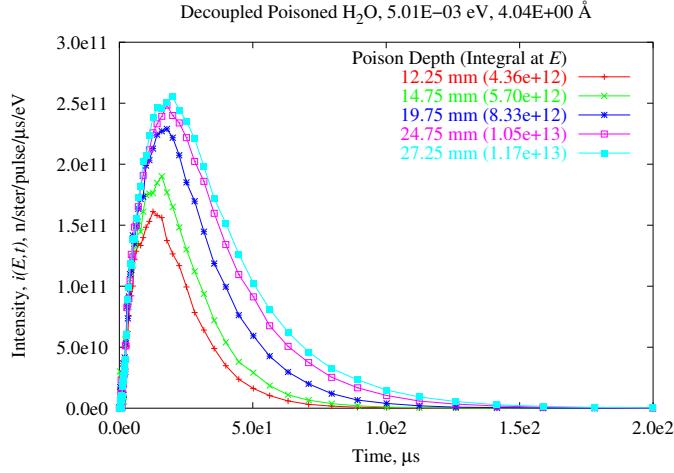
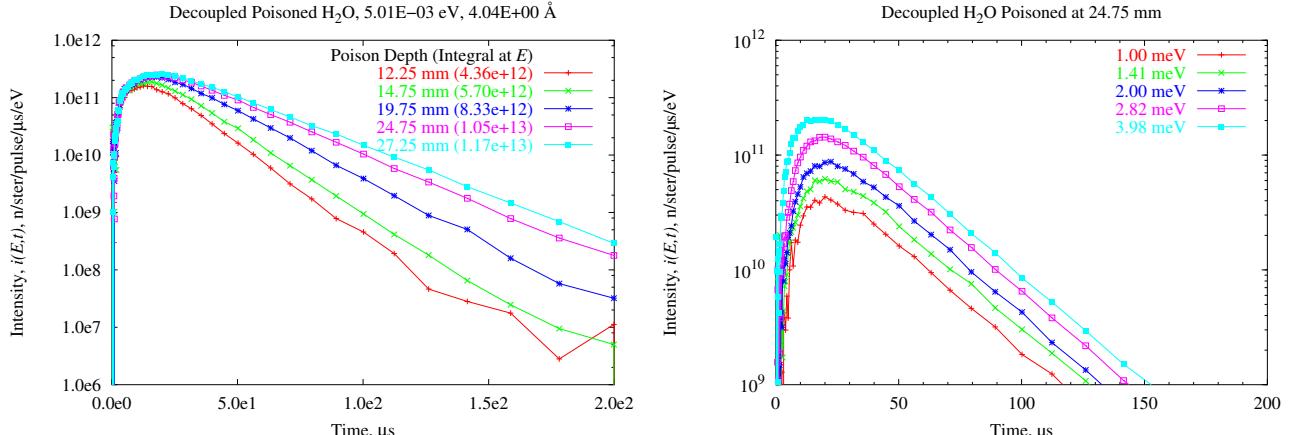


Figure 3: Emission time distributions for 5.01 meV neutrons from decoupled water moderators with different poison depths.

4 Parameterization

As described elsewhere¹ we use the function,

$$i(E) = I_{\text{epi}} e^{-c/\sqrt{E}} \left(R \frac{E}{(kT)^2} e^{-E/kT} + \Delta(E) \frac{1}{E^{1-\alpha}} \right), \quad (1)$$



(a) Multiple poison depths at a single energy.

(b) Multiple energies at a single poison depth.

Figure 4: Emission time distributions showing the thermalizing nature of water moderators.

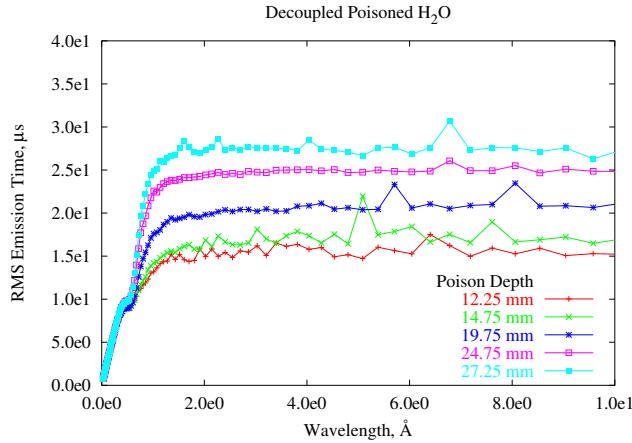


Figure 5: RMS Emission times for neutrons from a decoupled water moderator with different poison depths.

which combines a slowing-down spectrum and a Maxwellian using a generalized Westcott joining function $\Delta(E)$,

$$\Delta(E) = \frac{1}{1 + (E_{\text{co}}/E)^s}, \quad (2)$$

to fit the spectra from the water moderators, as shown in Figure 6. Discrepancies appear near 1–3 eV (as the slowing-down term does not allow for flux depressions near resonances in the gadolinium poison⁴) and at various energies from 3–30 meV (due to discretization artifacts in the $S(\alpha, \beta)$ treatment in MCNPX³). The term $e^{-c/\sqrt{E}}$ mimics the action of a $1/v$ absorber, although it does not correspond to attenuation due to material in the beamline. If this term were to be interpreted as absorption due to material in the neutron beamline (for example, the aluminum alloy forming the moderator vessel), it would imply approximately 1 m of aluminum in the beamline—which is obviously not the case. We attribute this behavior to a diffusion heating-like effect in the moderator material.

Parameters resulting from these fits are shown in Table 3. Although these parameterizations are inspired by a physics analysis of neutron slowing-down and thermalization, they do not model the simulated data well enough to have unique physical interpretations, and should be considered arbitrary “smoothing” functions. Although the general agreement appears good, χ^2_ν is high, typically around 400–2100. Although the quality of the fits shown in Figures 6 is only moderate, they can certainly be trusted to predict absolute performance to better than 10% over the energy range 0.001–10 eV, and to predict relative trends to somewhat better precision.

References

- [1] E. B. Iverson, P. D. Ferguson, F. X. Gallmeier, and I. I. Popova, “Detailed SNS neutronics calculations for scattering instrument design: SCT configuration,” Tech. Rep. SNS 110040300-DA0001-R00, Oak Ridge National Laboratory, July 2002.
- [2] L. S. Waters, “MCNPX™ user’s manual,” Tech. Rep. LA-UR 99-6058, Los Alamos National Laboratory, November 1999.

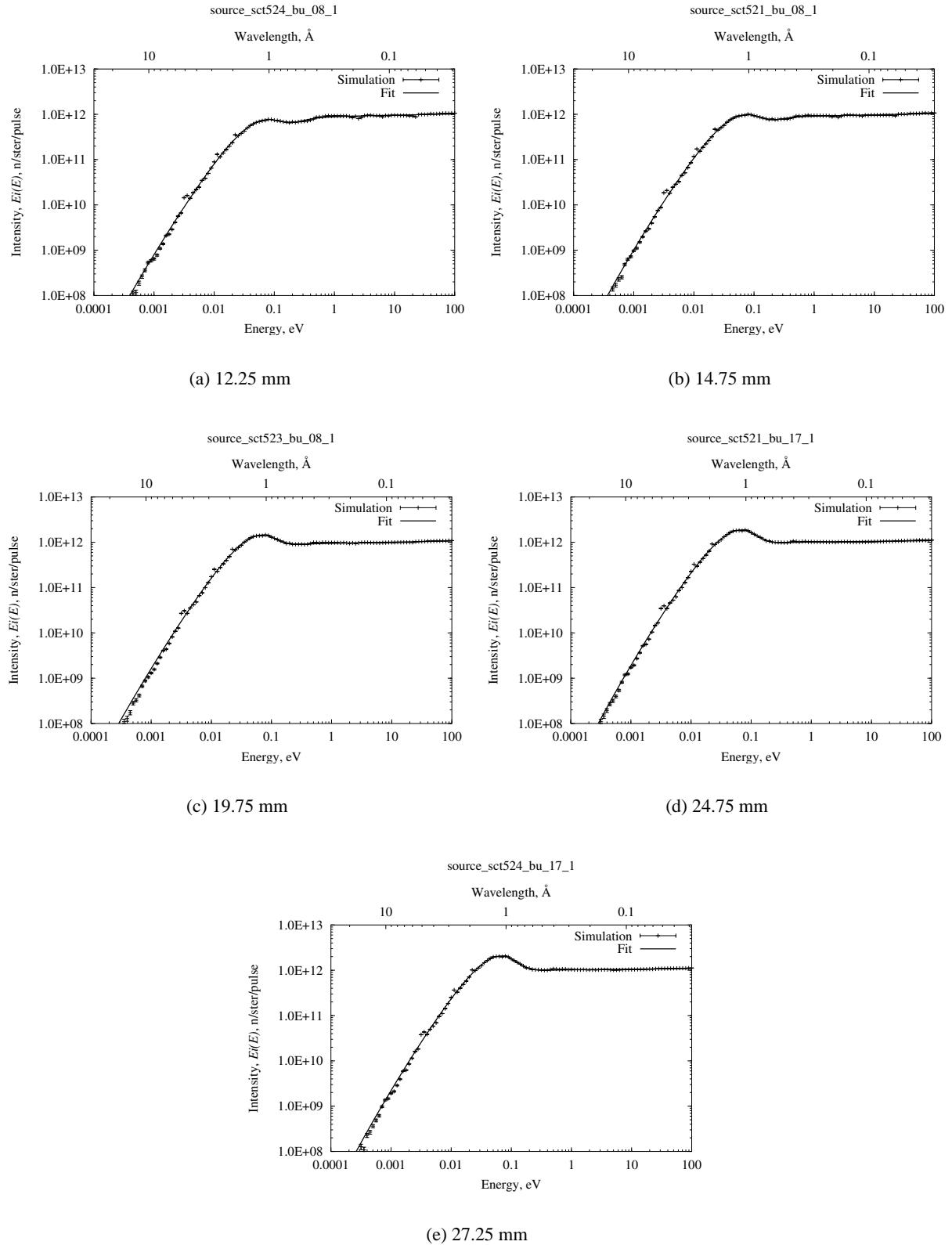


Figure 6: Parametric fits to the spectral intensities from water moderators of different poison depths.

Poison Depth	Moderator	I_{epi} n/ster/eV/pulse	kT meV	R -	c $\sqrt{\text{eV}}$	E_{co} meV	s -	α -
12.25	dec. pois. H ₂ O	9.1×10^{11}	32.	1.33	0.013	143.	1.19	0.026
14.75	dec. pois. H ₂ O	9.3×10^{11}	32.	1.86	0.016	136.	1.82	0.025
17.25	dec. pois. H ₂ O	9.5×10^{11}	33.	2.40	0.013	149.	2.77	0.024
19.75	dec. pois. H ₂ O	9.6×10^{11}	34.	2.88	0.012	153.	3.52	0.023
19.75	dec. pois. H ₂ O	10.0×10^{11}	32.	2.79	0.021	144.	2.81	0.014
22.25	dec. pois. H ₂ O	10.2×10^{11}	33.	3.20	0.019	150.	3.40	0.013
24.75	dec. pois. H ₂ O	10.3×10^{11}	33.	3.58	0.017	155.	3.89	0.012
27.25	dec. pois. H ₂ O	10.4×10^{11}	33.	3.89	0.015	158.	4.24	0.011

Table 3: Spectral parameterizations of decoupled water moderator performances.

- [3] R. E. MacFarlane, “Cold-moderator scattering kernel methods,” in *Proceedings of the International Workshop on Cold Moderators for Pulsed Neutron Sources* (J. M. Carpenter and E. B. Iverson, eds.), pp. 221–231, OECD, 1998.
- [4] E. B. Iverson and B. D. Murphy, “Burn-up of moderator poison in pulsed neutron sources,” in *Proceedings of the 4th International Topical Meeting on Nuclear Applications of Accelerator Technology, AccApp’00*, pp. 109–115, American Nuclear Society, November 2000.

A Data Availability

These results are available electronically as “source files;” ASCII files containing the spectra and emission time distributions, with comments showing the file format. Each moderator–poison depth combination is represented by a single source file. These source files can be downloaded from <http://www.sns.anl.gov> under “Components/Moderators.” Various “metrics” characterizing the spectra and pulse shapes are sometimes more useful than the fully detailed source. We have calculated the following metrics for each neutron beam:

- total intensity,
- peak intensity,
- peak time,
- full-width at half-maximum,
- mean emission time, and
- root-mean-square emission time.

These metrics are also available at the same location. Datasets are associated with source files and metrics files as given in Table 4. Note that additional source files for other poison depths not plotted (for reasons of space) are also available.

Poison Depth (mm)	Moderator	Source File	Metrics File
12.25	dec. pois. H ₂ O	source_sct524_bu_08_1.dat	source_sct524_bu_08_1_metrics.dat
14.75	dec. pois. H ₂ O	source_sct521_bu_08_1.dat	source_sct521_bu_08_1_metrics.dat
17.25	dec. pois. H ₂ O	source_sct522_bu_08_1.dat	source_sct522_bu_08_1_metrics.dat
19.75	dec. pois. H ₂ O	source_sct523_bu_08_1.dat	source_sct523_bu_08_1_metrics.dat
19.75	dec. pois. H ₂ O	source_sct523_bu_17_1.dat	source_sct523_bu_17_1_metrics.dat
22.25	dec. pois. H ₂ O	source_sct522_bu_17_1.dat	source_sct522_bu_17_1_metrics.dat
24.75	dec. pois. H ₂ O	source_sct521_bu_17_1.dat	source_sct521_bu_17_1_metrics.dat
27.25	dec. pois. H ₂ O	source_sct524_bu_17_1.dat	source_sct524_bu_17_1_metrics.dat

Table 4: Source file and metrics file names.

B Detailed Spectra and Pulse Shapes

Some of the detailed spectra and pulse shapes as produced with the simulations appear below. These plots represent only a fraction of the information available from the detailed source and metrics files.

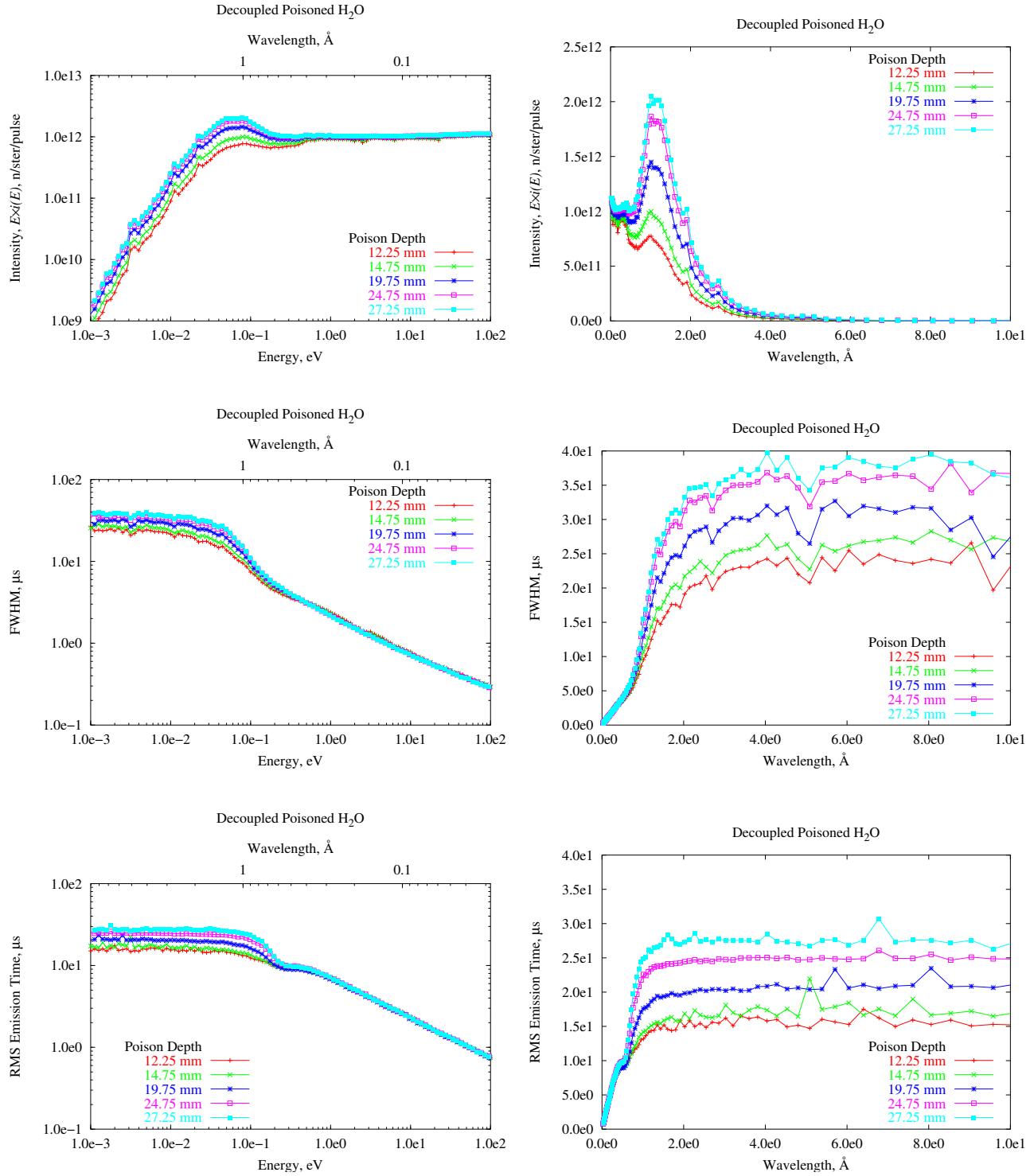


Figure 7: Intensity and pulse widths (FWHM and RMS) for decoupled water moderators.

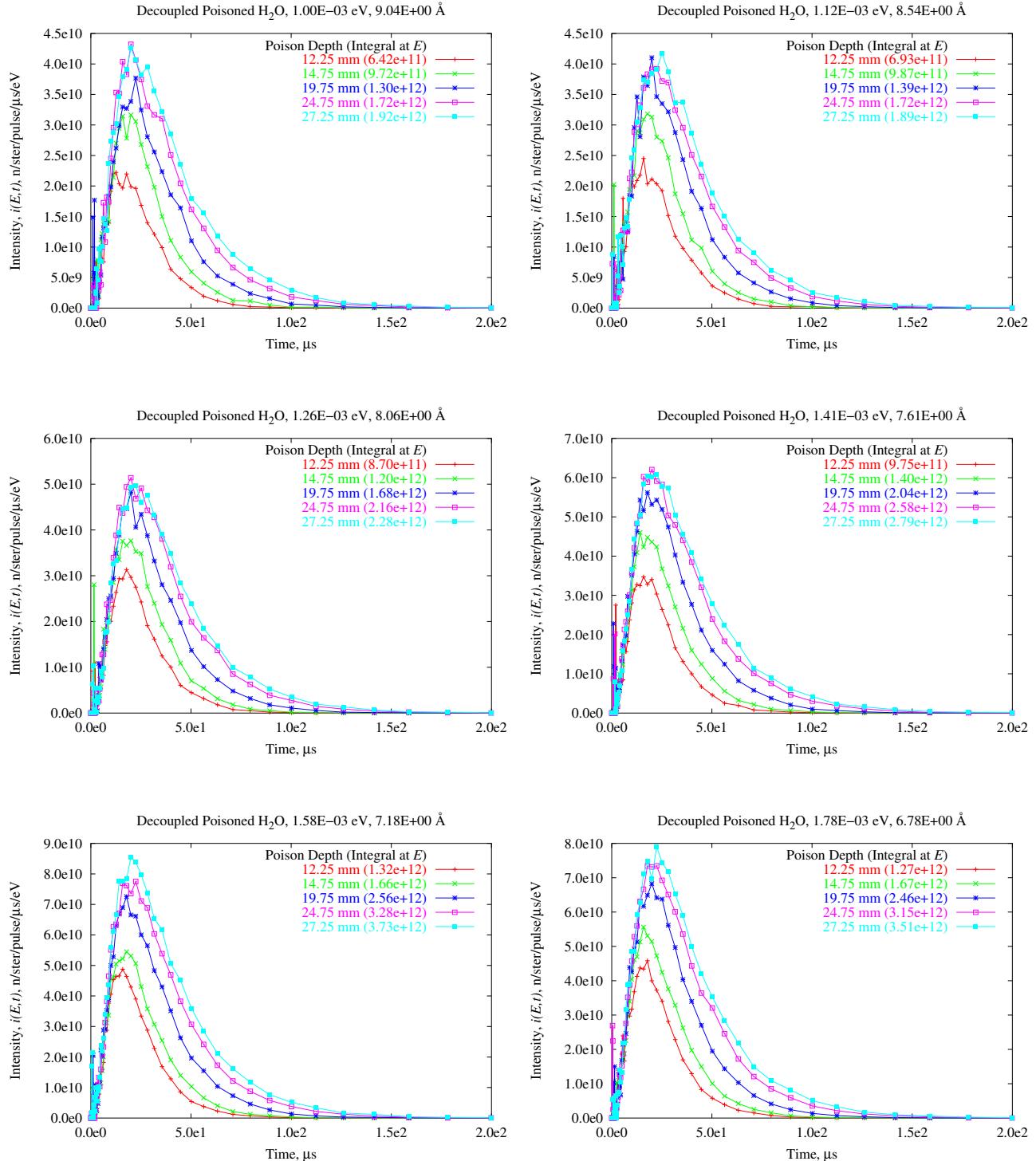


Figure 8: Emission time distributions for decoupled water moderators with different poison depths.

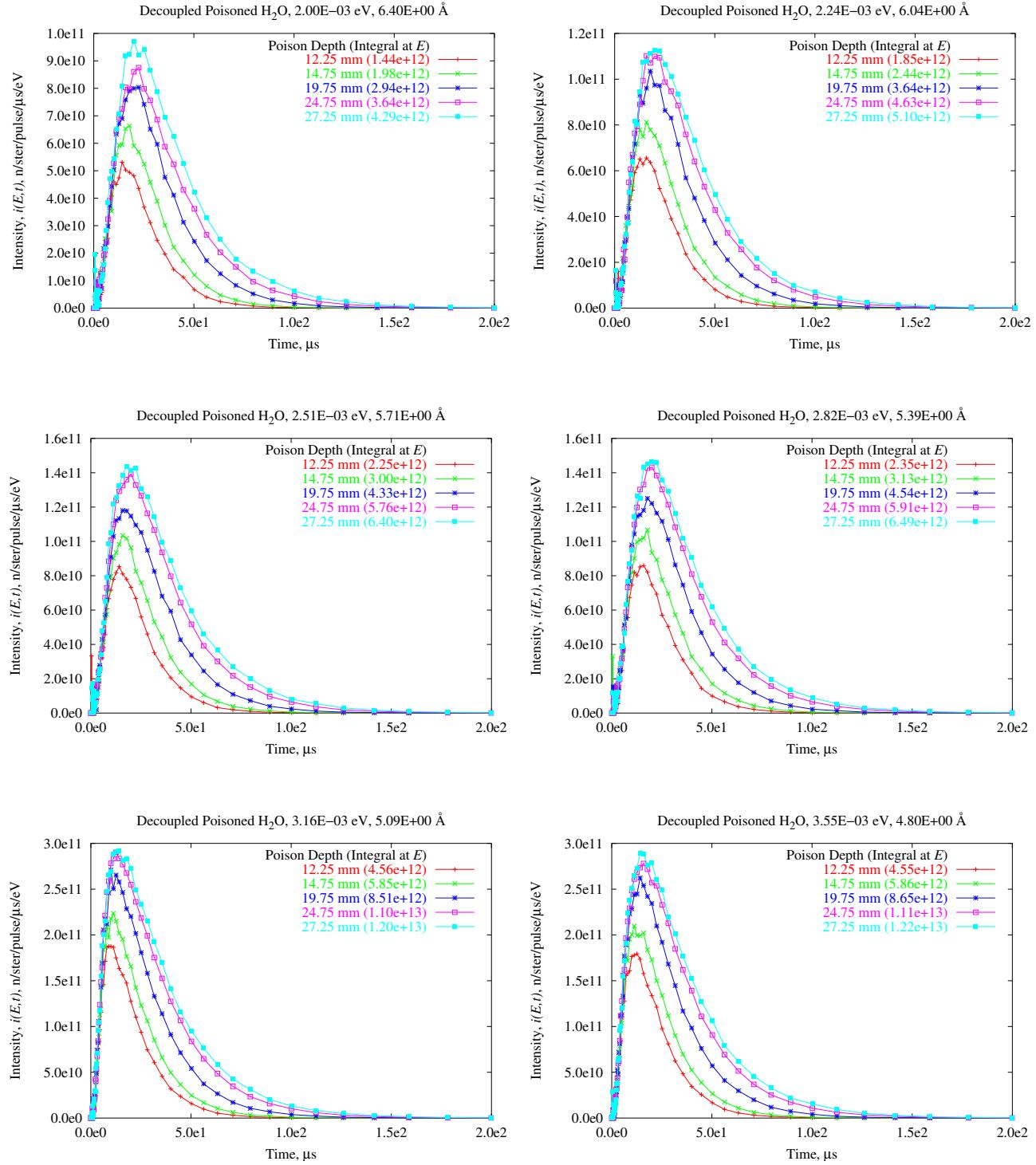


Figure 9: Emission time distributions for decoupled water moderators with different poison depths.

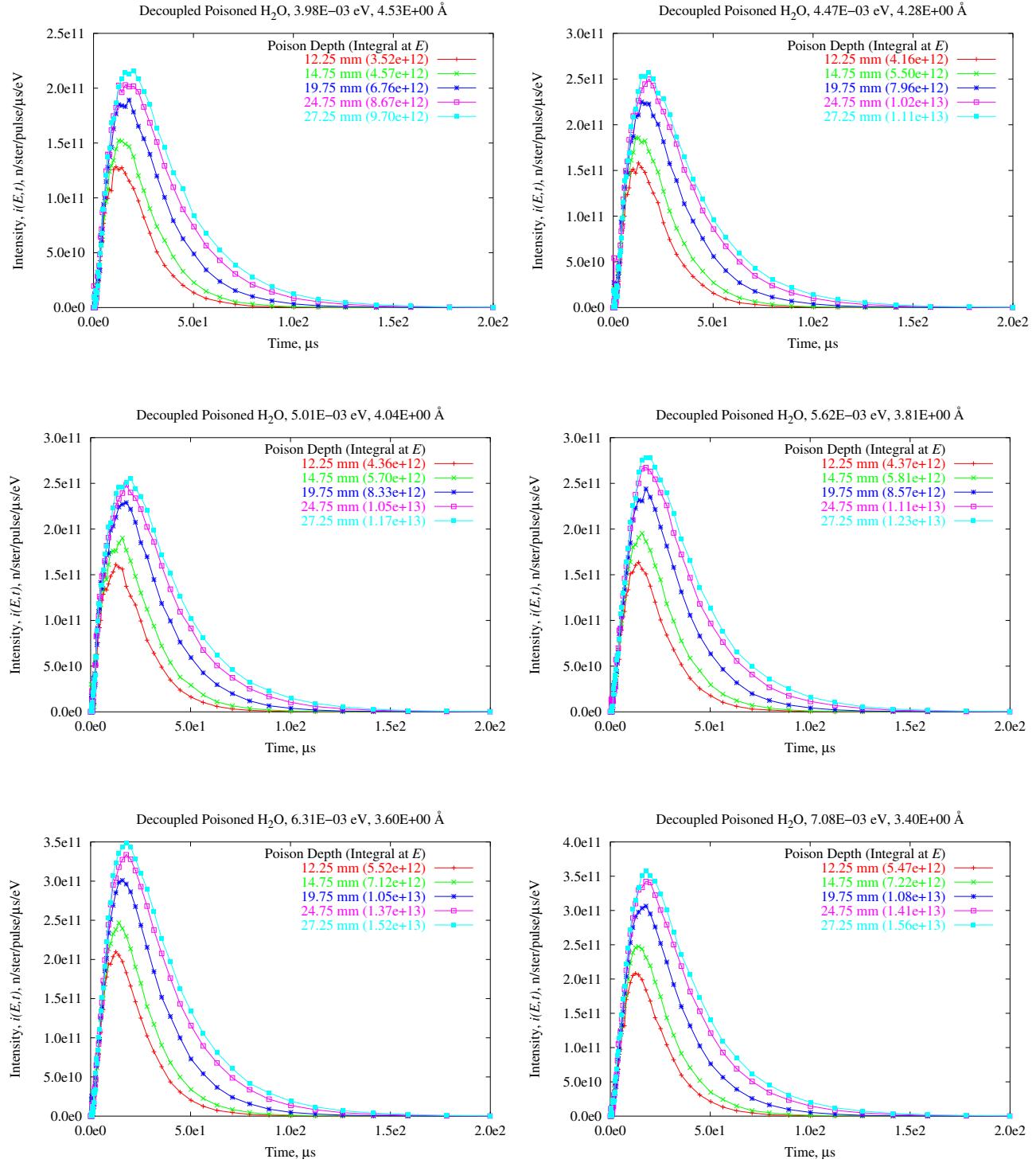


Figure 10: Emission time distributions for decoupled water moderators with different poison depths.

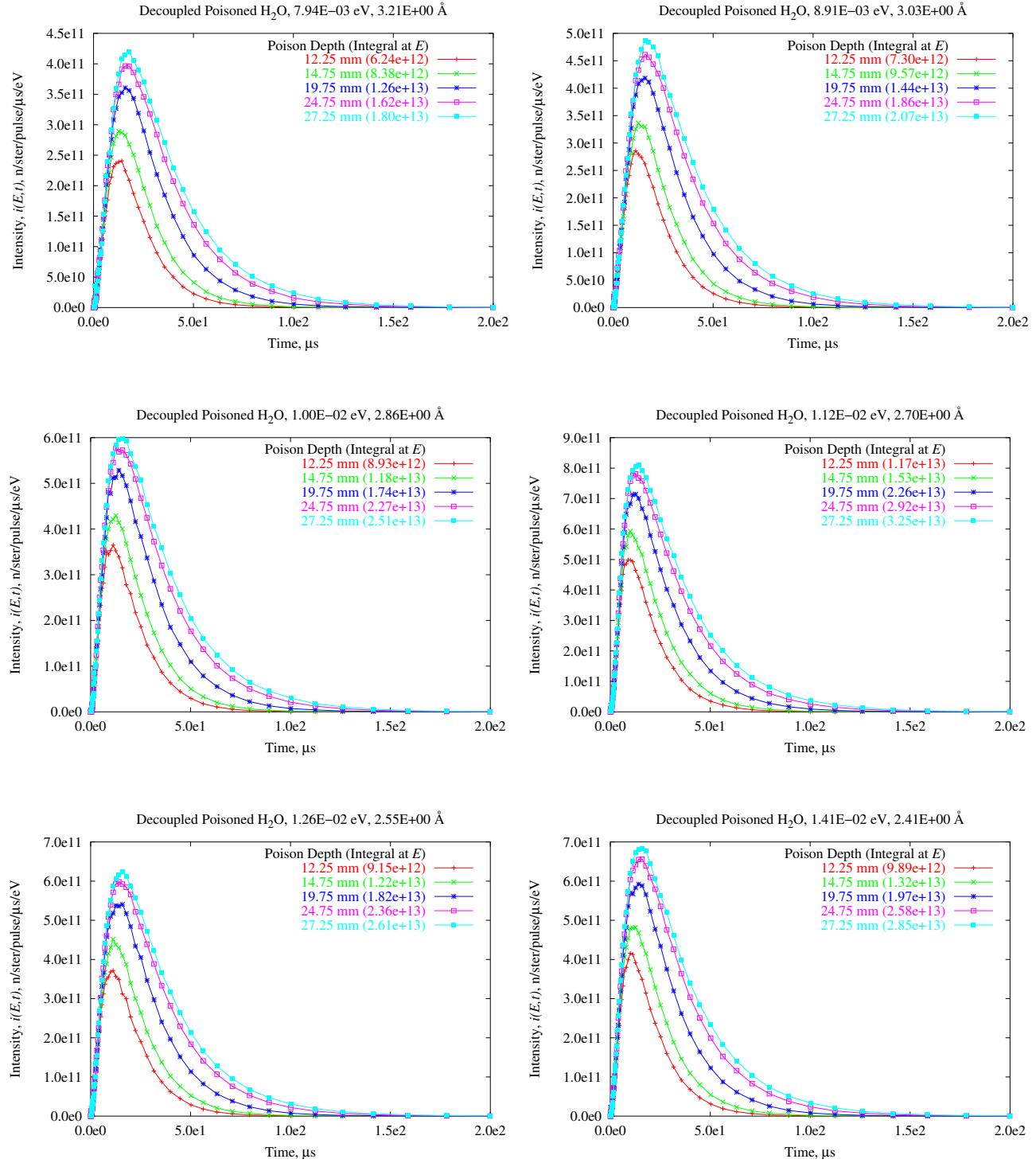


Figure 11: Emission time distributions for decoupled water moderators with different poison depths.

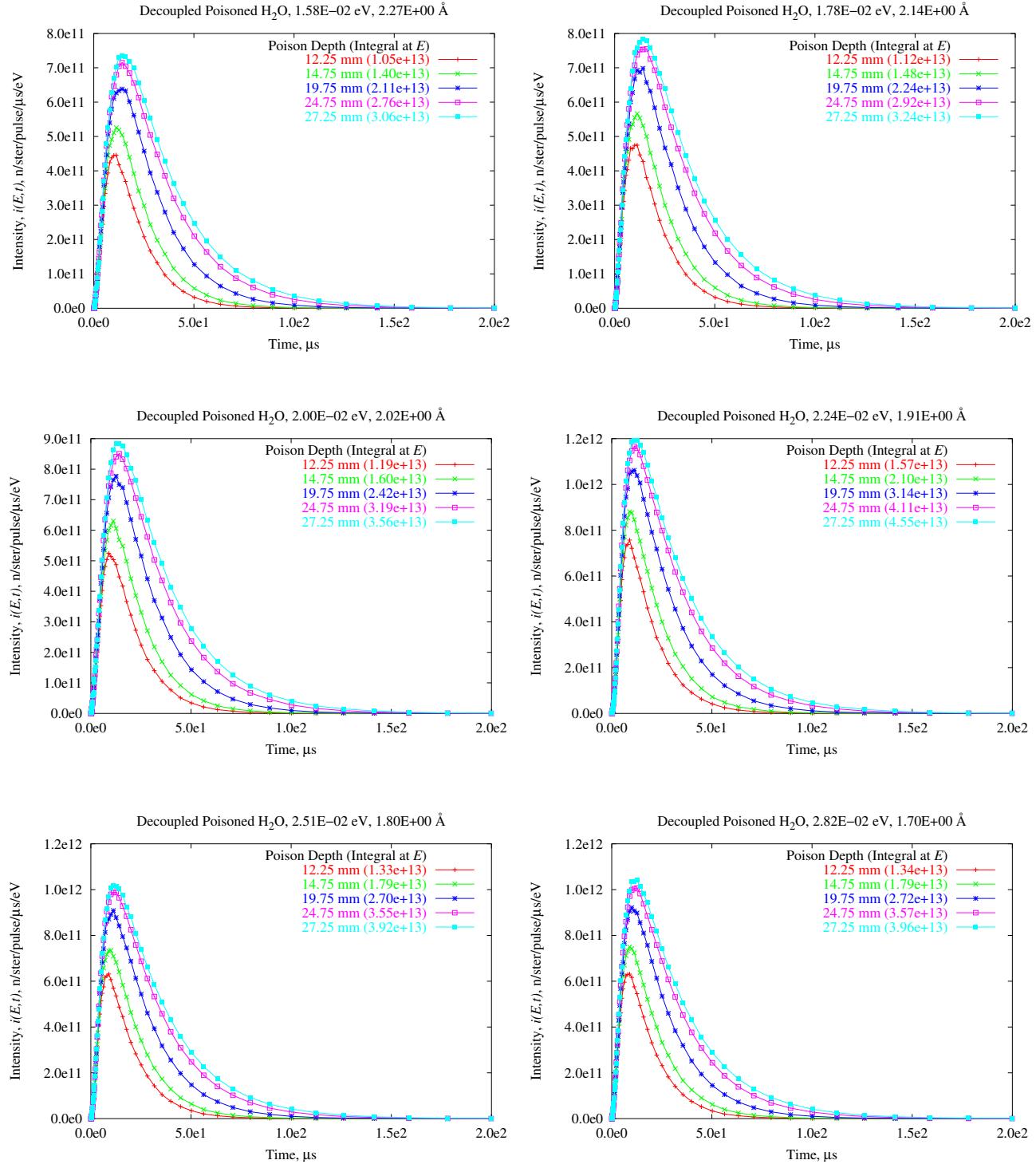


Figure 12: Emission time distributions for decoupled water moderators with different poison depths.

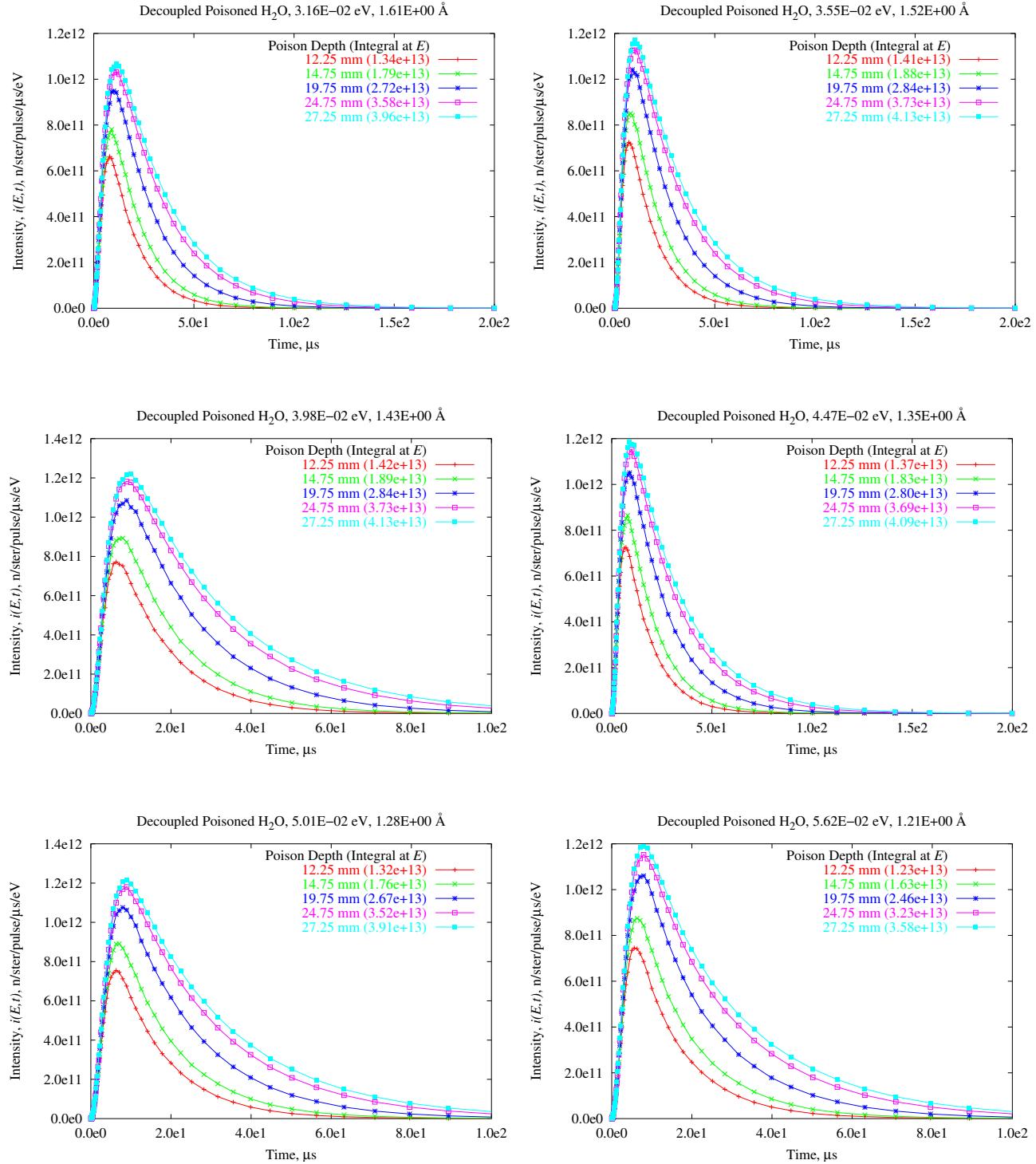


Figure 13: Emission time distributions for decoupled water moderators with different poison depths.

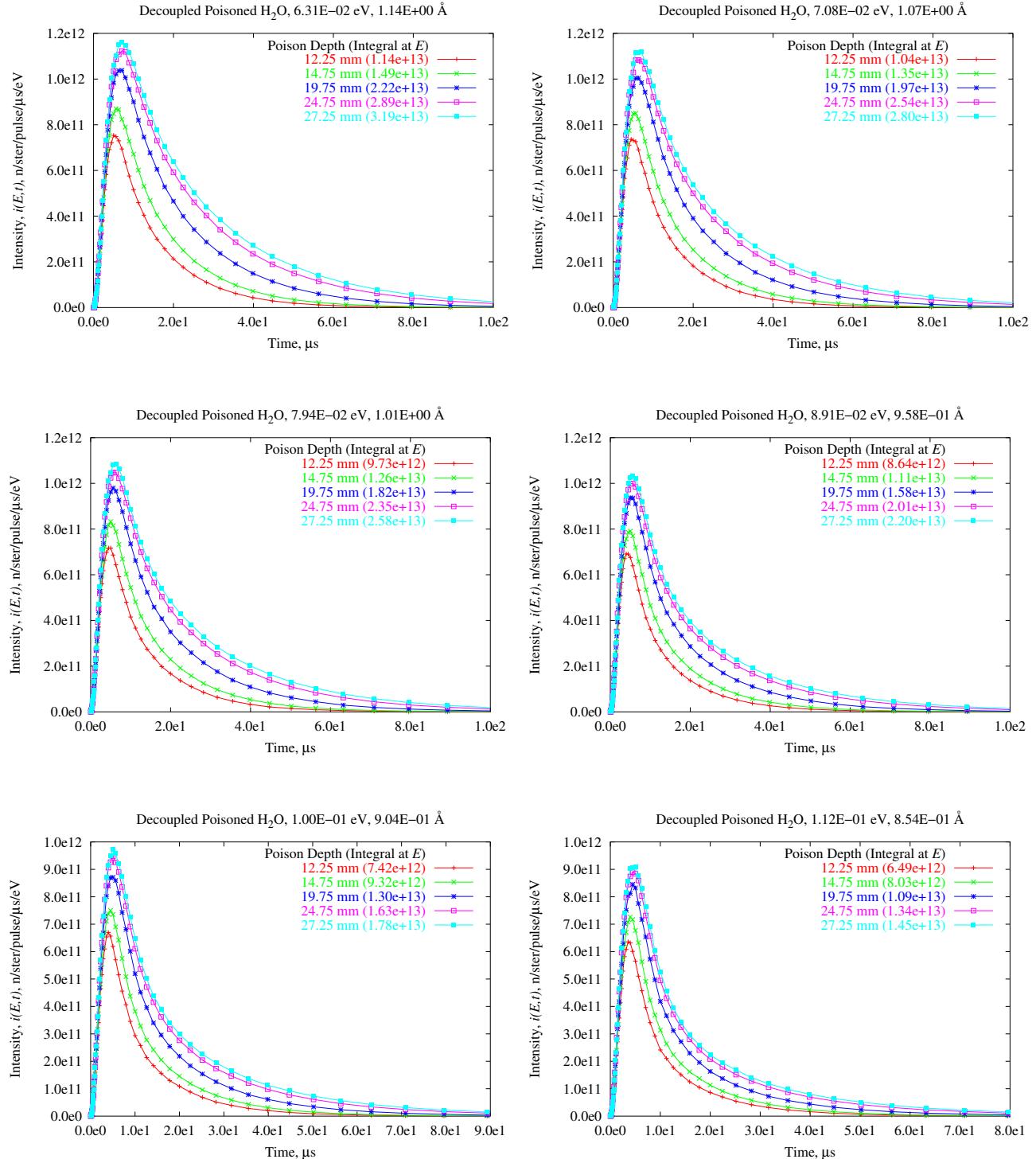


Figure 14: Emission time distributions for decoupled water moderators with different poison depths.

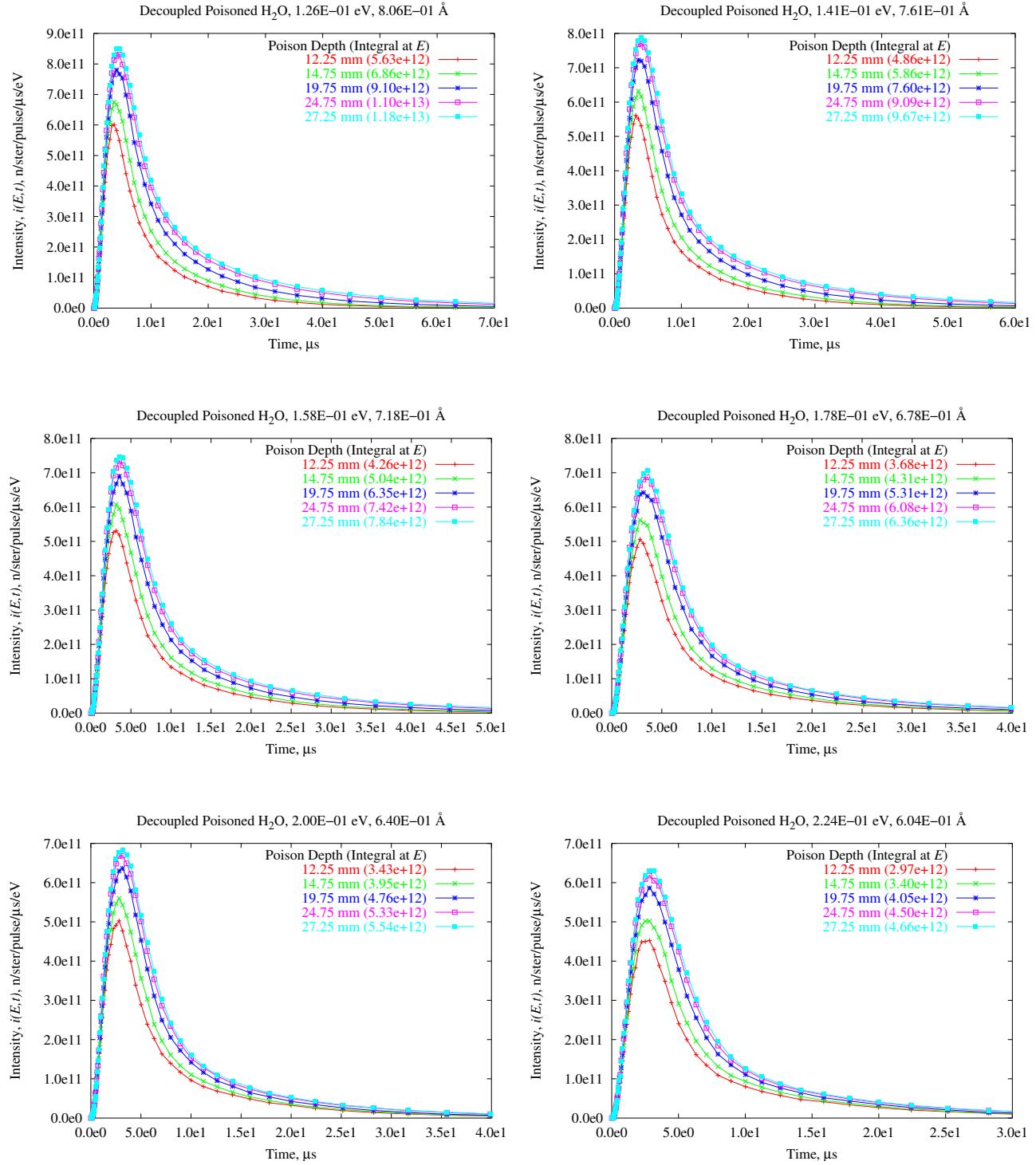


Figure 15: Emission time distributions for decoupled water moderators with different poison depths.

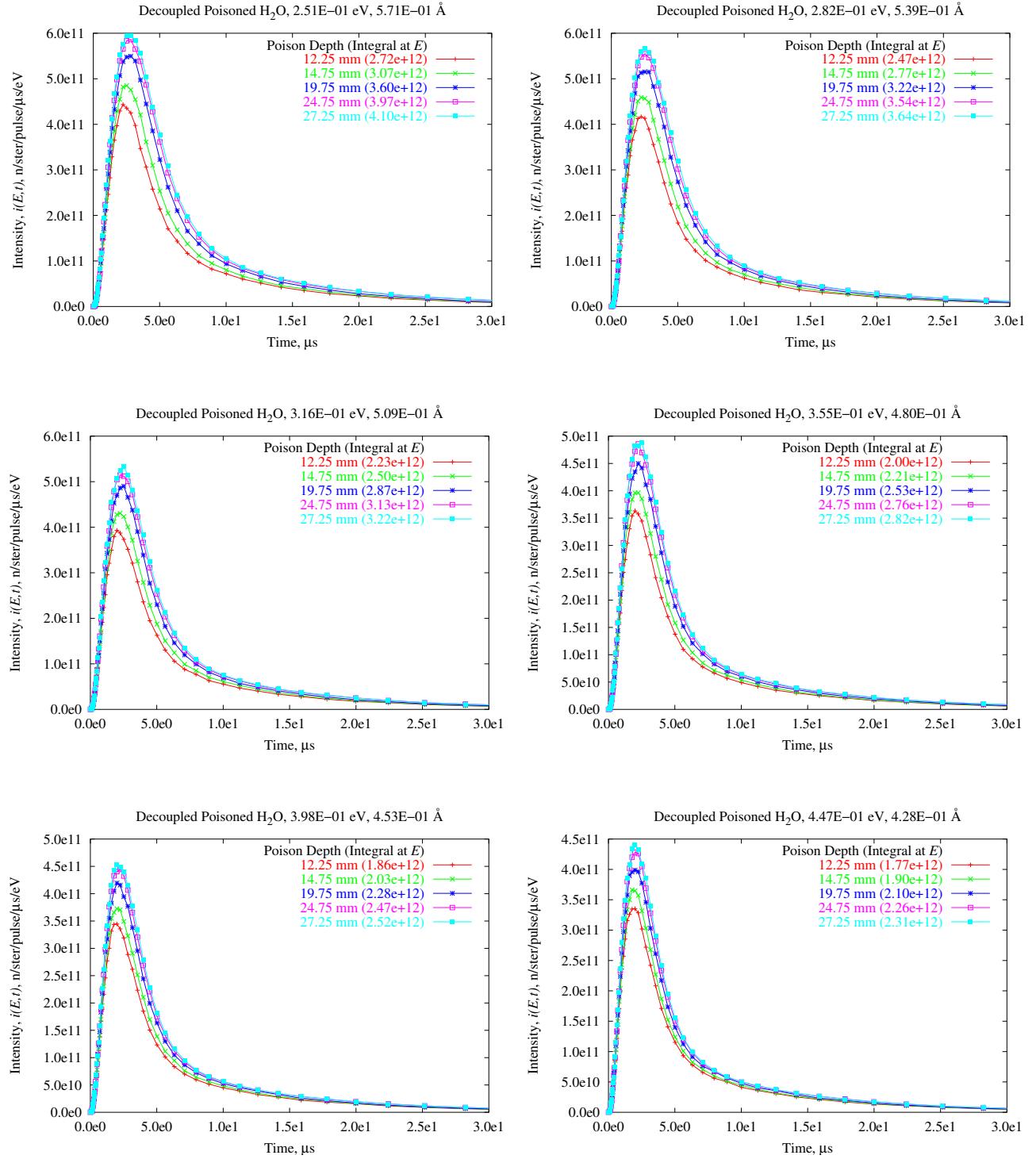


Figure 16: Emission time distributions for decoupled water moderators with different poison depths.

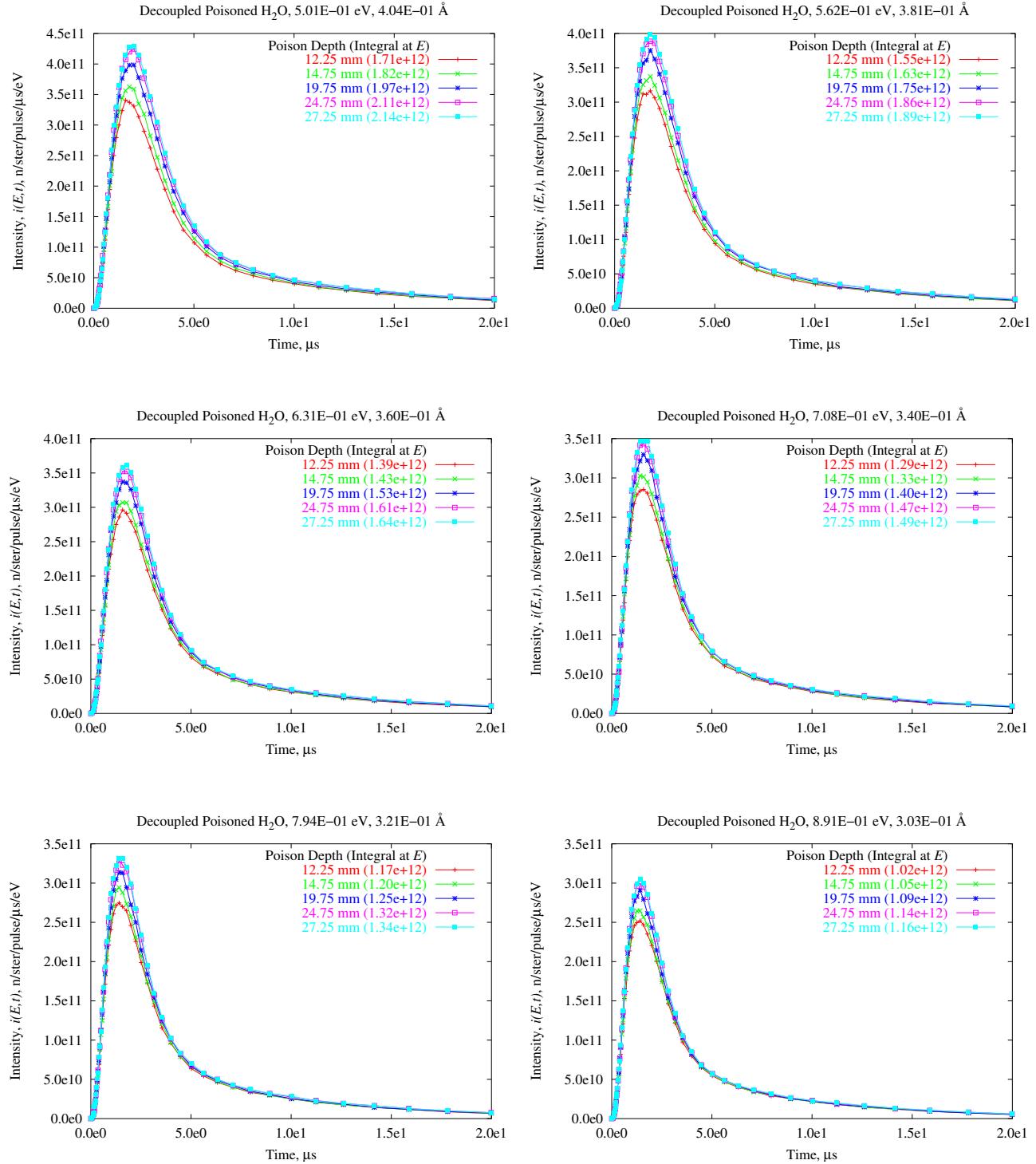


Figure 17: Emission time distributions for decoupled water moderators with different poison depths.

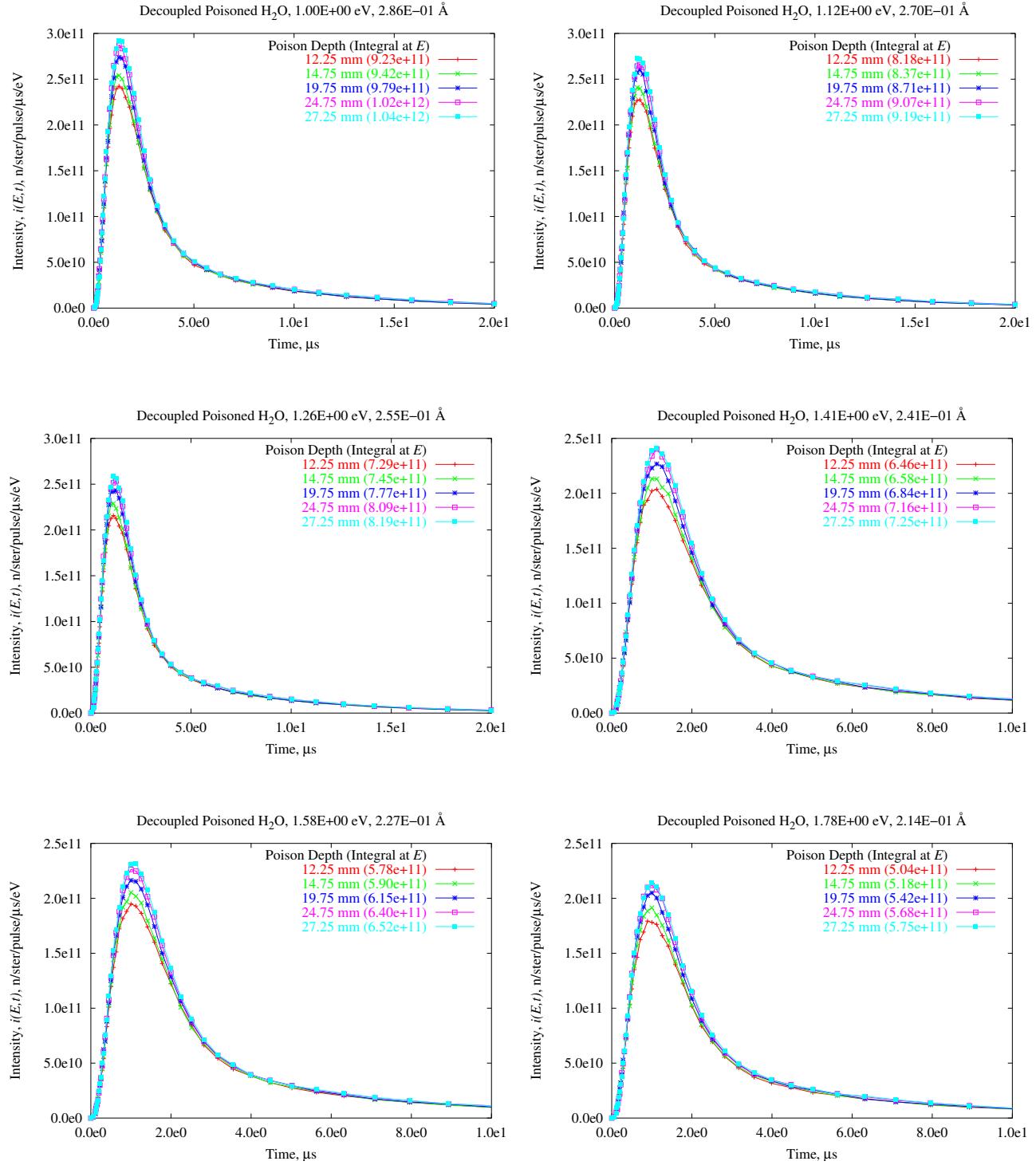


Figure 18: Emission time distributions for decoupled water moderators with different poison depths.

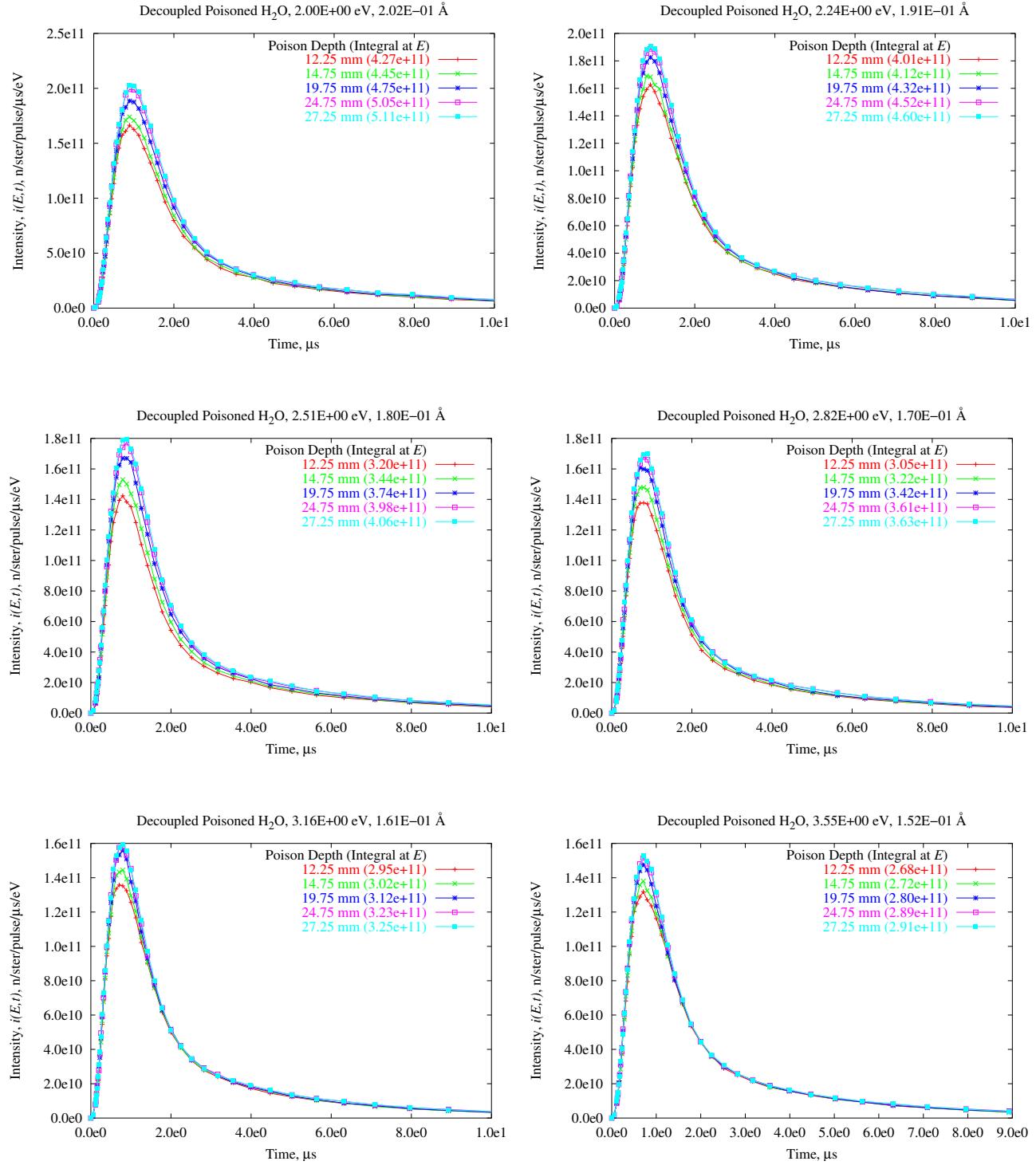


Figure 19: Emission time distributions for decoupled water moderators with different poison depths.

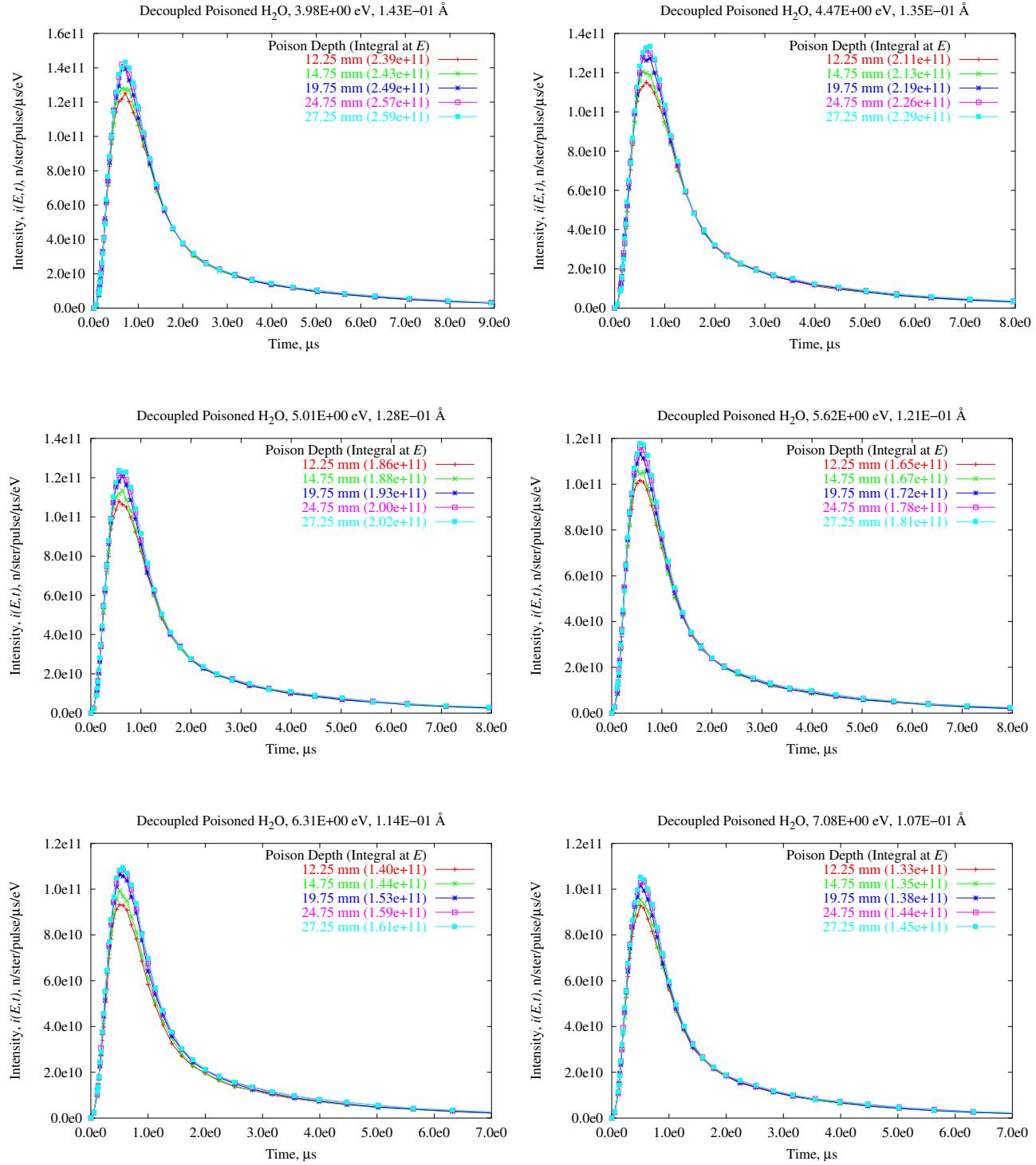


Figure 20: Emission time distributions for decoupled water moderators with different poison depths.

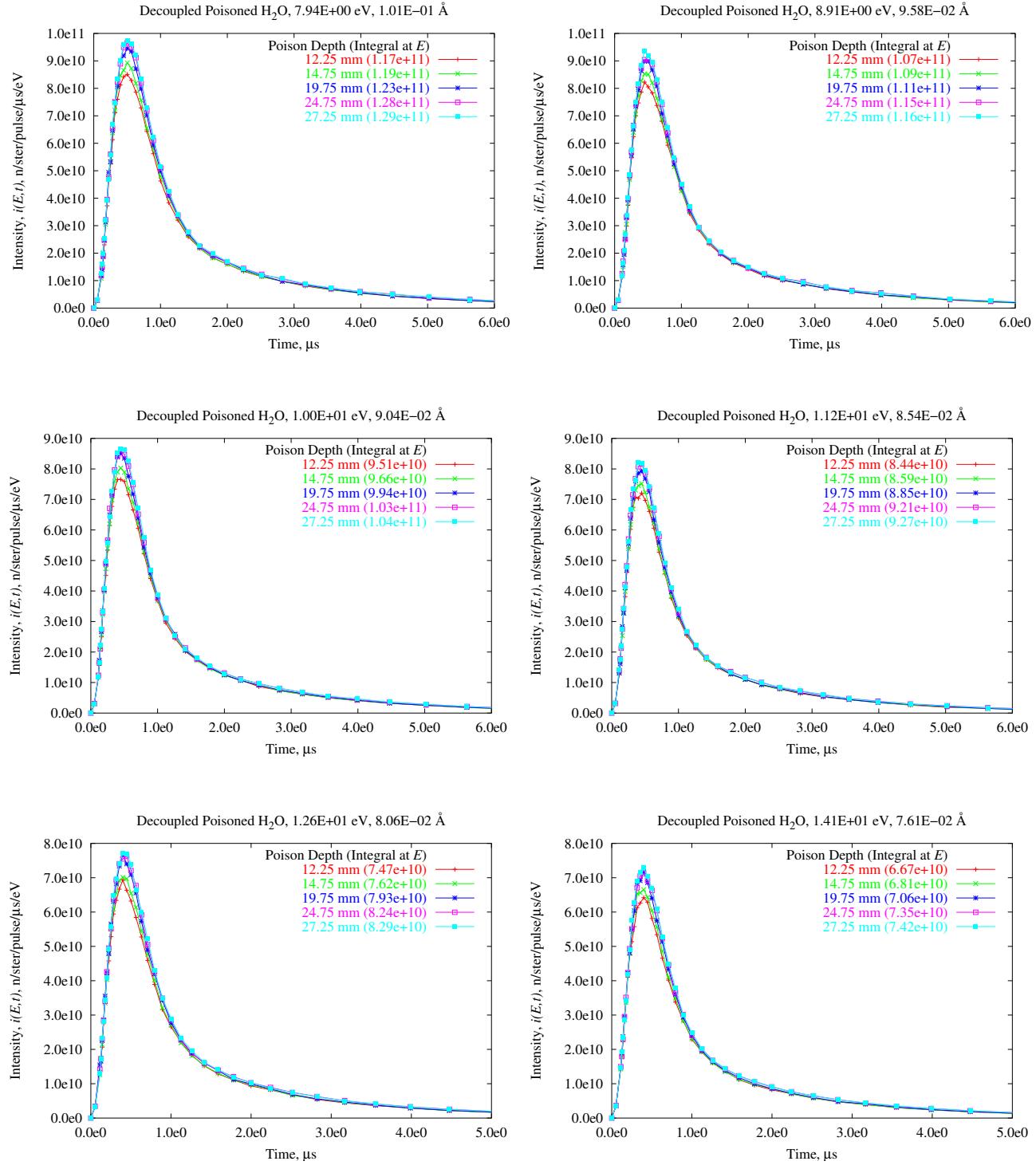


Figure 21: Emission time distributions for decoupled water moderators with different poison depths.